Synthesis of Juvenile and Adult Salmon Studies at the Hiram M. Chittenden Locks

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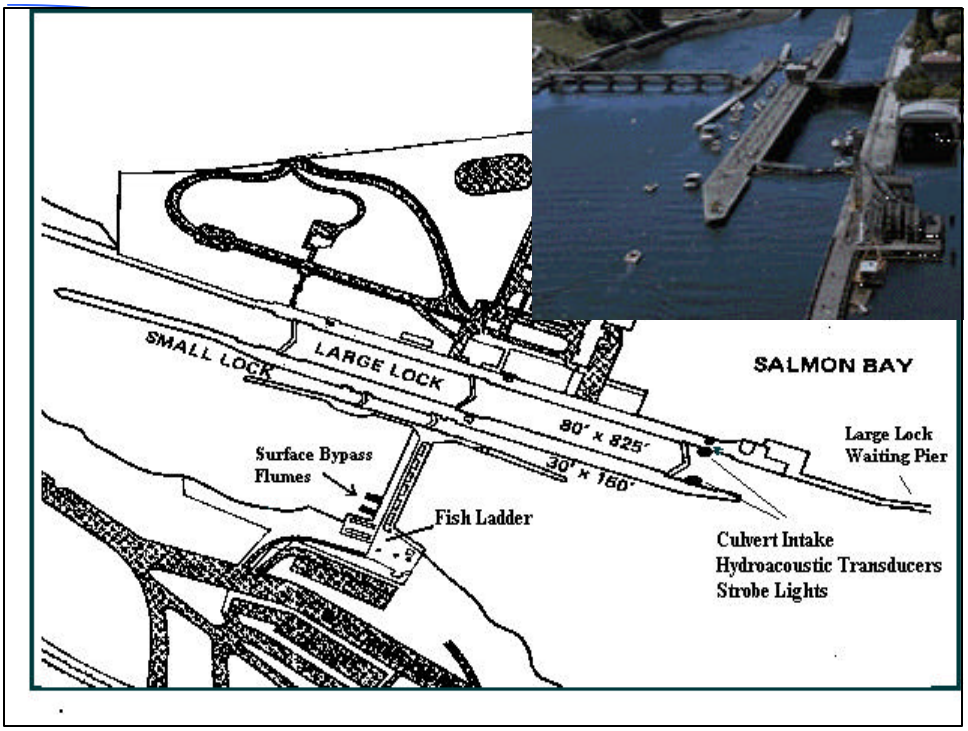
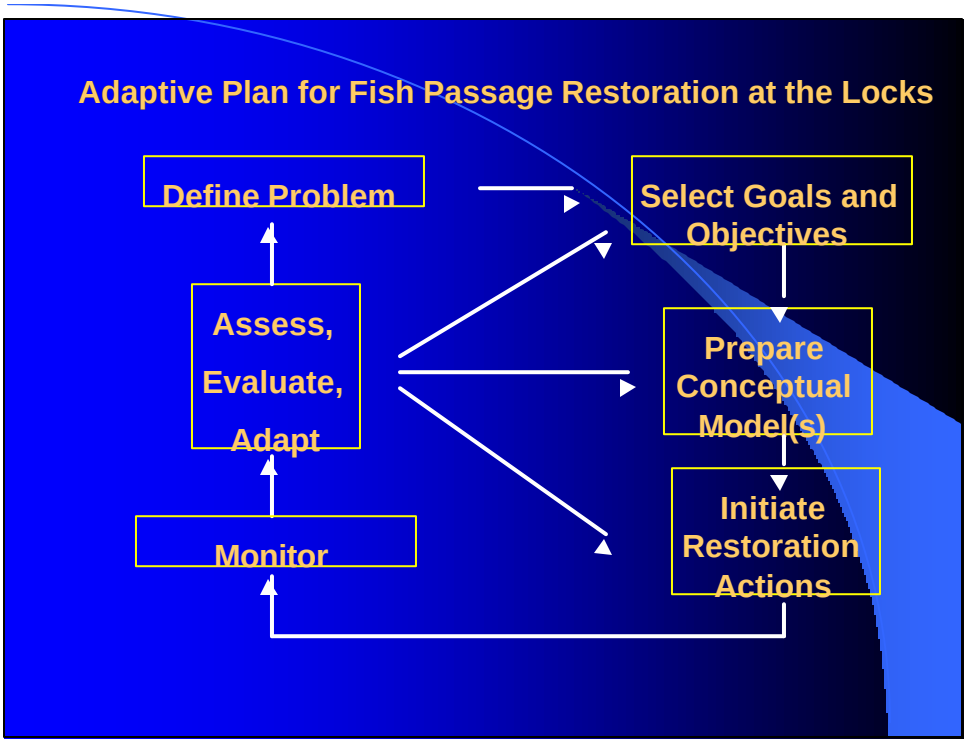
Purpose: Synthesis of Juvenile and Adult Salmon Studies at the Locks

1. Juvenile Fish Passage
   a. Review the Project as an Adaptive Management Experiment.

2. Adult Fish Passage.
   a. Provide overview of adult behavior.
   b. Describe development of a coupled ecological model that links water quality modeling to a fish behavior model.


SMALL LOCK
LARGE LOCK
SALMON BAY
80' x 825'
30' x 160'
Large Lock
Waiting Pier
Surface Bypass
Flumes
Fish Ladder
Culvert Intake
Hydroacoustic Transducers
Strobe Lights


Adaptive Plan for Fish Passage Restoration at the Locks
Define Problem
Select Goals and Objectives
Assess, Evaluate, Adapt
Prepare Conceptual Model(s)
Initiate Restoration Actions
Monitor

Adaptive Management Elements:

- Hypothesis Development through baseline monitoring.
- Hypothesis Testing through controlled experiments and evaluation.
- Development of Restoration Project Objectives, Features, and Planned Post Construction Monitoring.
- Performance Measurements to verify if we met our project objectives and to prove or disprove our restoration hypotheses.

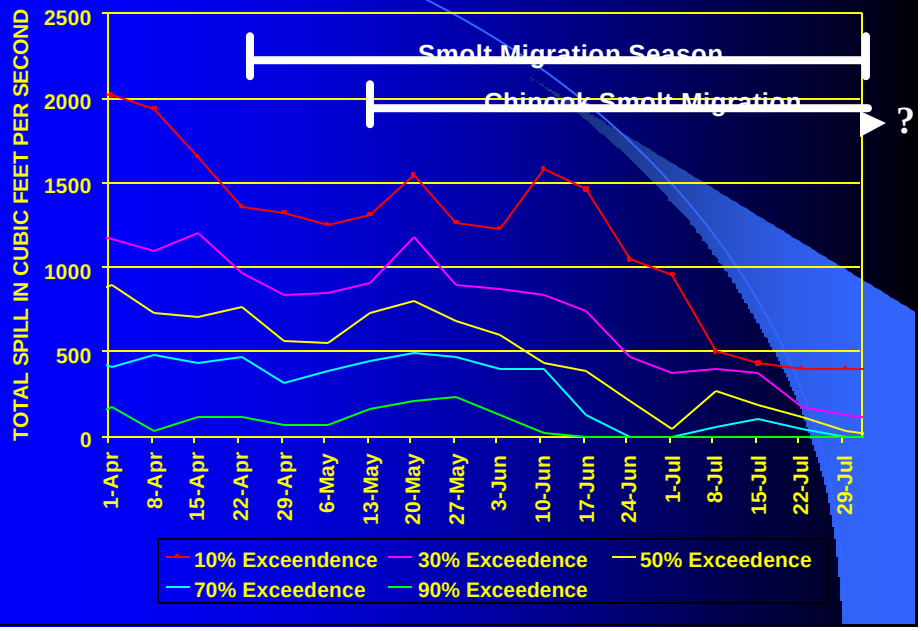
History of Passage Experiments

* 1994 Slow Fill Experiment by Lockmasters
* 1995 Prototype Low flow Flume @ 80 cfs
* 1996 Begin Monitoring Entrainment in L. Lock
* 1997 Experiment with Low Frequency Sound
* 1997 Netpen Testing of Sound and Light
* 1998 Monitor Slowfill in L. Lock
  Test Strobe Lights
* 2000 4 New Flumes@400 cfs; Slowfill as SOP; Removed Barnacles; installed Strobe Lights; Begin use of Passive integrated transponders
* 2002 Begin use of Strobe Lights
* 2003Testing of Micro-acoustic tags

Surface Bypass Development

- Problem: Prior to 1994, little water was spilled during the smolt outmigration season in May through July. Juvenile salmon were found dead and injured below the Locks.
- Hypothesis: A low flow (80-100 cfs) smolt passage flume will provide enough flow to pass juvenile salmon.
- History: The first surface bypass collectors aka smolt passage flumes was built on a Corps dam in Oregon in 1994. The concept of a surface weir and flume was highly experimental at that time.
- Experiment: The Corps used design specifications of that collector and built a prototype weir/flume for approximately $80,000 in 1995. The flume was monitored from 1995-1998.
- Result: Juvenile salmon immediately used the flume, up to 20,000 smolts were counted using the flume at the peak day.
- Adaptive Action: The prototype flume became the design basis for 4 new permanent flumes (total of 400 cfs) installed in 2000.

How Much Water? When?
Summary Hydrograph for Available Spill



Spillway : prototype flume 1995-1999 and four new flumes 2000

Prototype

4 New Flumes

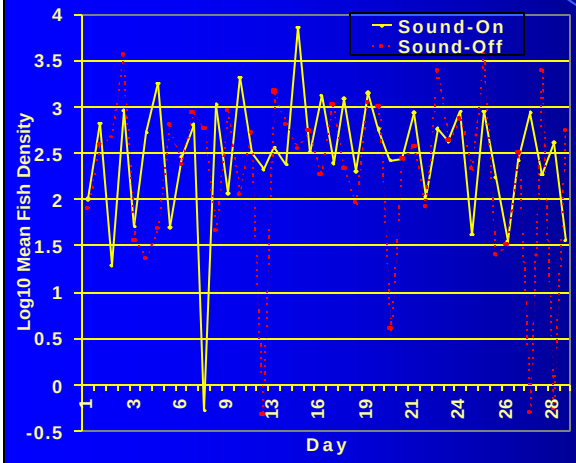
Behavioral Guidance Technology

- **Problem: Prior to 1994, little water was spilled during the smolt outmigration season in May through July and large numbers of smolts were entrained in the lock culverts. The lock was also used at an unusual frequency from 1982-1994 (miniflushing).**
- **Hypothesis: Sensory stimuli (low frequency sound, constant light, strobe light, or reduced velocity) can guide juvenile salmon away from the filling culverts reducing entrainment by 50%.**
- **History: Prior to testing at the Locks, no field experiment had achieved a conclusive behavioral guidance test of juvenile salmon.**
- **Overall Experiments: Small scale testing (net pen) of sound and lights was conducted in 1997 at the Locks. Full scale deployment of sound and strobe lights was conducted in 1997 and 1998. Slow fill of the large lock was tested in 1998, 2000, and 2001.**

Behavioral Guidance Technology

- **Sound Guidance Experiment:** Low frequency sound (300-400 hZ) with 104 paired trials of sound on and sound off were conducted in May and June 1997 in front of the large lock entrance.
- Result: Fish density was 15% lower with sound on but the difference was not significantly different.
- Adaptive Action: Low frequency sound was eliminated as a potential restoration action.
- **Strobe Light Experiment:** Described previously. Proof of concept occurred in 1997 and 1998. Full field experiment occurred in 2002 during sockeye and coho emigration.
- Result: Fish density was 75% lower with strobe lights which was significantly different than with sound off.
- Adaptive Action: Strobe lights will be implemented as a standard operating procedure in 2003. Further testing will occur to determine effectiveness at night and during chinook emigration.

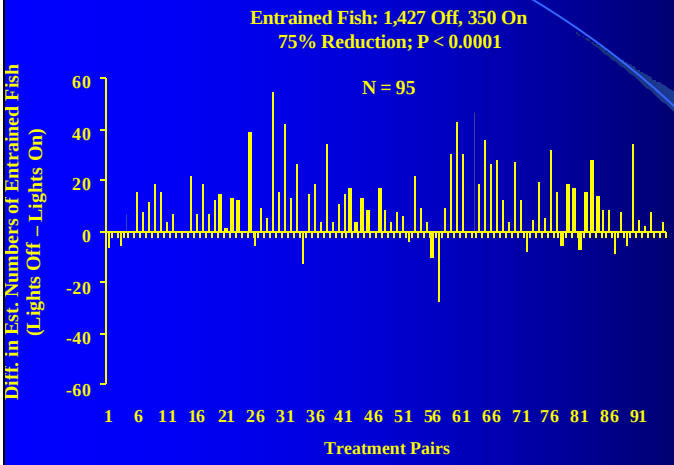
Low-Frequency Sound Test Results -- 1997



The sound treatment did not impact the density of salmonids measured within the lock chamber.

- The 300/400 Hz has been evaluated at three locations: Georgiana Slough; Bonneville Dam; Hiram M. Chittenden Large Lock and WES Net Pen tests
- To date, there has been little evidence of directed movement by the 300/400 Hz sound blending
- WES Net Pen tests showed a startle response at 150-200 Hz
- We recommend against using low frequency sound technology at the 300/400 Hz range
- The Locks is a semi-controlled, small scale testing facility that could be used to evaluate other behavioral technologies

Strobe Lights - Results



- Strobe lights were highly effective in reducing fish entrainment into the large lock filling culverts during periods when sockeye and coho were the predominant out-migrants
- Entrainment was not confined to just daylight hours, and habituation to strobe lights appears to have occurred

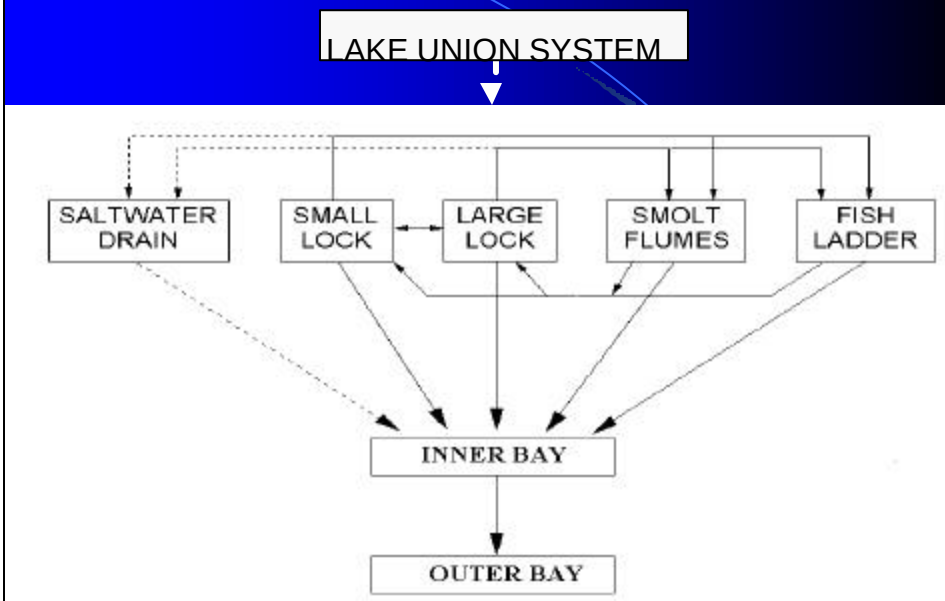
Behavioral Guidance Technology

- Slow Fill Experiment: Baseline monitoring of smolt entrainment on standard fill procedures occurred in the upper lock chamber in 1996 and 1998. In 2000, three levels of slow fill (5 minute, 10 minute, and 14 minute fill time) were monitored (using a random block design) by purse seining in the Lock Chamber. A total of 20 fills/treatment were monitored. Performance measure is fish catch per unit effort.
- Result: Purse seining showed catch was 40% lower at the 10 minute fill (27 fish/fill) and 60% lower at 14 minutes (17 fish/fill). Hydroacoustic estimates matched the 10 minute catch and showed no difference in entrainment rate between the 10 and 14 minute fills (29.8 and 29.3 fish respectively).
- Adaptive Action: Miniflushing was discontinued in 1994. Fill rate was first reduced in 1998. Slow fill (10 minute) of the lock chamber is now a standard operating procedure. The lock valve motors are scheduled for replacement beginning in 2003 allowing slower fill rates to be evaluated as another action to reduce entrainment rate. Slow fill has also been implemented as a protection measure for juvenile salmon on navigation locks in the Columbia River.

Develop Restoration Actions

- Experiments and Monitoring results led to development of a conceptual model of fish passage, identification of project objectives, elements, new hypotheses and additional experiments for a new restoration project at the Locks.
- Project Objectives
  - Increase smolt use of the spillway.
  - Reduce entrainment into the filling culverts.
  - Reduce injury if entrainment reduction is not completely successful.
- Project Elements
  - Four smolt passage flumes - total 400 cfs
  - Slow fill of the large lock - Experimental
  - Barnacle Removal - Experimental
  - Strobe light - Experimental

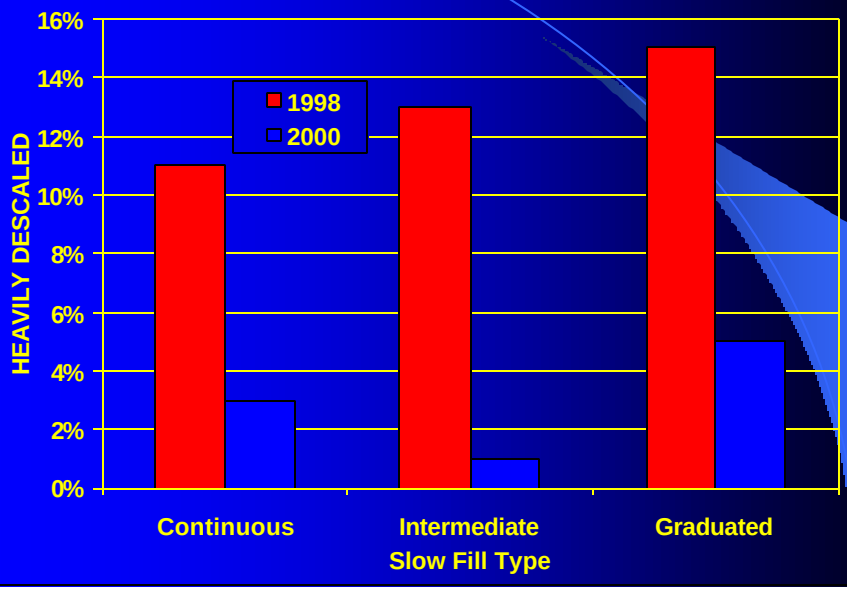
Conceptual Model of Fish Passage Routes



Injury Reduction: Barnacle Removal

- Problem: Baseline monitoring showed that during operation of the prototype flume (80-100 cfs) up to 60% of all fish were still entrained in the lock filling culverts with 13% of these fis heavily descaled and 65% lightly descaled.
- Hypothesis: Smoothing of the rough surfaces on the lock walls will reduce descaling by 50%. A linked hypothesis – slower fill rates will reduce velocity and thereby reduce descaling.
- History: No other project to our knowledge has the problem of barnacles encrusting conduits that pass juvenile salmon.
- Experiment: Baseline injury rate monitoring occurred in 199 Barnacles were removed in November 1999. Post-treatment monitoring occurred in 2000.
- Result: Heavy descaling of fish was 75% lower after barnacl removal (13% descaled before, 3% after). There was a slight increase in descaling (5% vs 3%) at the slowest fill rates.
- Adaptive Action: Barnacle removal during dewatering each year is now a standard operating procedure.

Barnacle Removal: Comparison of Heavy Descaling Before (1998) and After (2000)

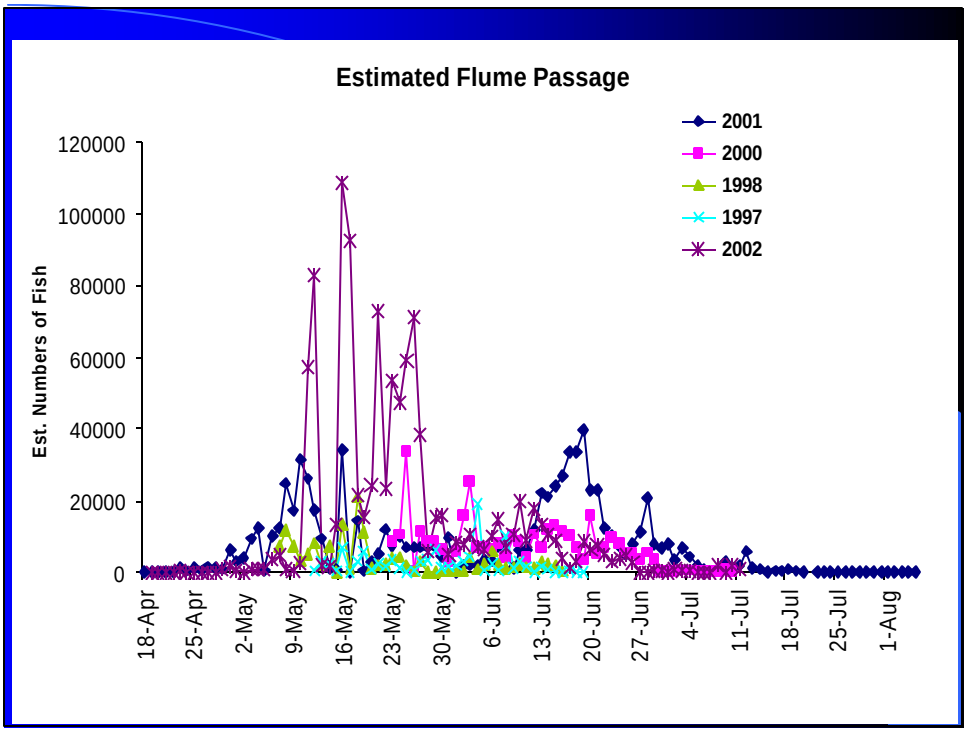


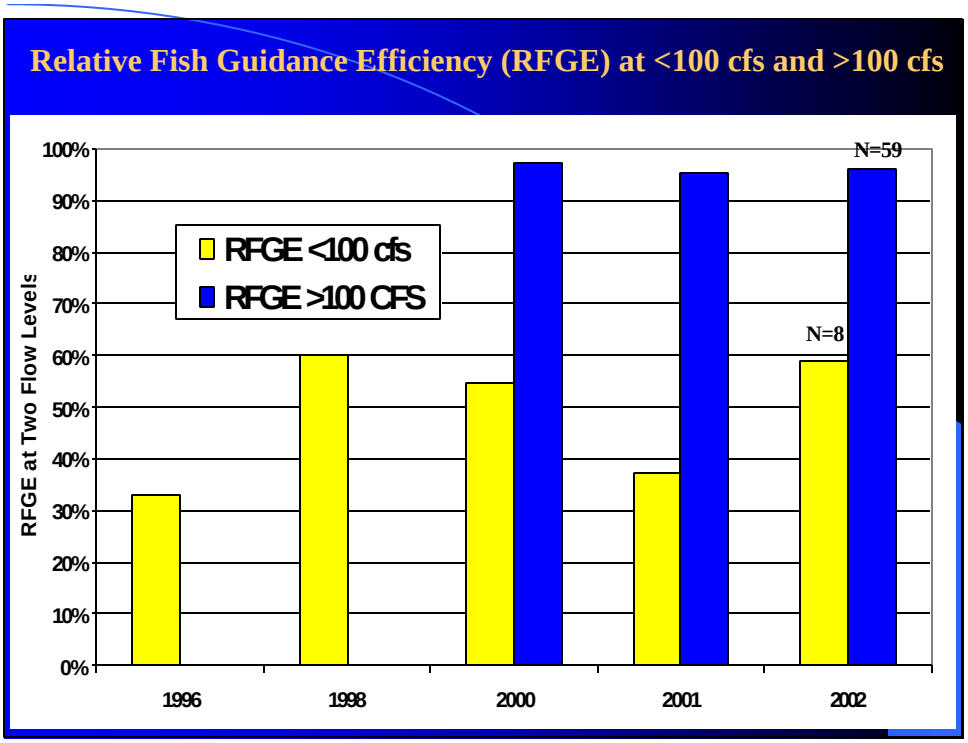
Surface Bypass Development

- Revised Hypothesis: Smolt passage flumes will pass 65% or more of all smolts migrating through the project.
- History: The total water volume passed over the flumes increased from 100 cfs to 400 cfs in 2000. The highest previous RFGE at 100 cfs was 60% in 1998.
- Experiment: All four flumes began operation in 2000 with varying degrees of operation based on flume volume. PIT-tag monitors were suspended in a cantilever fashion, the only installation of this type in the world.
- Result: Flume counts increased from maximum one day count of 20,000 fish (prototype <100 cfs) to 110,000 (400cfs - 2002). RFGE has improved from 33% and 60% (1996, 1998) at <100 cfs to 96-98% (2000-2002) at>100 cfs. RFGE remains below 60% at flows <100 cfs (2000-2002). Periods with low RFGE are few (example,n=8 in 2002), occur late in season coincident with high temperatures and total smolt numbers. PIT-tag monitoring has defined chinook migration and may provide a unique predictive tool (lunar phase) to forecast timing of smolt passage water needs months in advance.

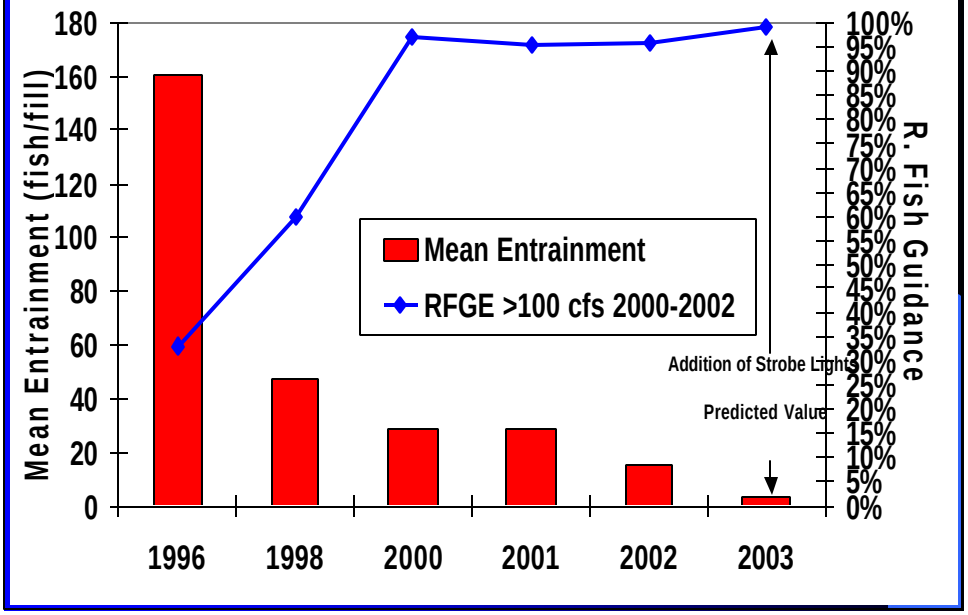
Surface Bypass Development

- Adaptive Action: Revised Hypothesis: What is the minimum flow volume necessary to pass 95-99% of all smolts.
- Monitoring requirements – Conduct a second year of randomized flume operation between high and low flow and utilize calibration of observes to improve accuracy.
- Evaluate chinook behavior later in season (how do they respond to higher temperatures and low flow) with alternative technology –microacoustic tags, which could provide survival estimates through the project irrespective of pathway taken.

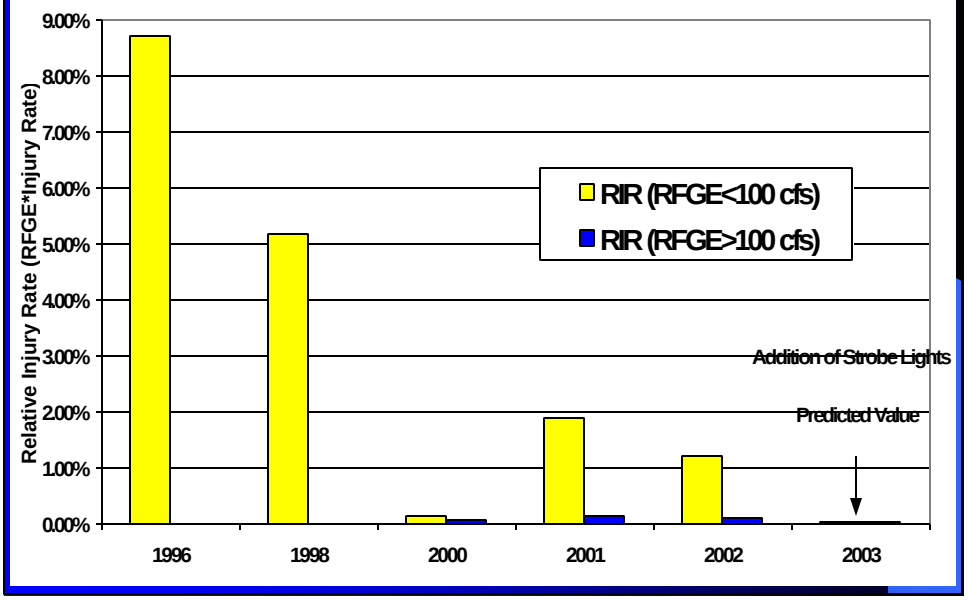

Estimated Flume Passage
2001
2000
1998
1997
2002
Est. Numbers of Fish
120000
100000
80000
60000
40000
20000
0
18-Apr
25-Apr
2-May
9-May
16-May
23-May
30-May
6-Jun
13-Jun
20-Jun
27-Jun
4-Jul
11-Jul
18-Jul
25-Jul
1-Aug


Relative Fish Guidance Efficiency (RFGE) at <100 cfs and >100 cfs
RFGE at Two Flow Levels
RFGE <100 cfs
RFGE >100 CFS
N=59
N=8
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1996
1998
2000
2001
2002

Mean Entrainment Rate and RFGE



Relative Injury Rate (RIR) = RFGE * Injury Rate



Other Indicators of Performance

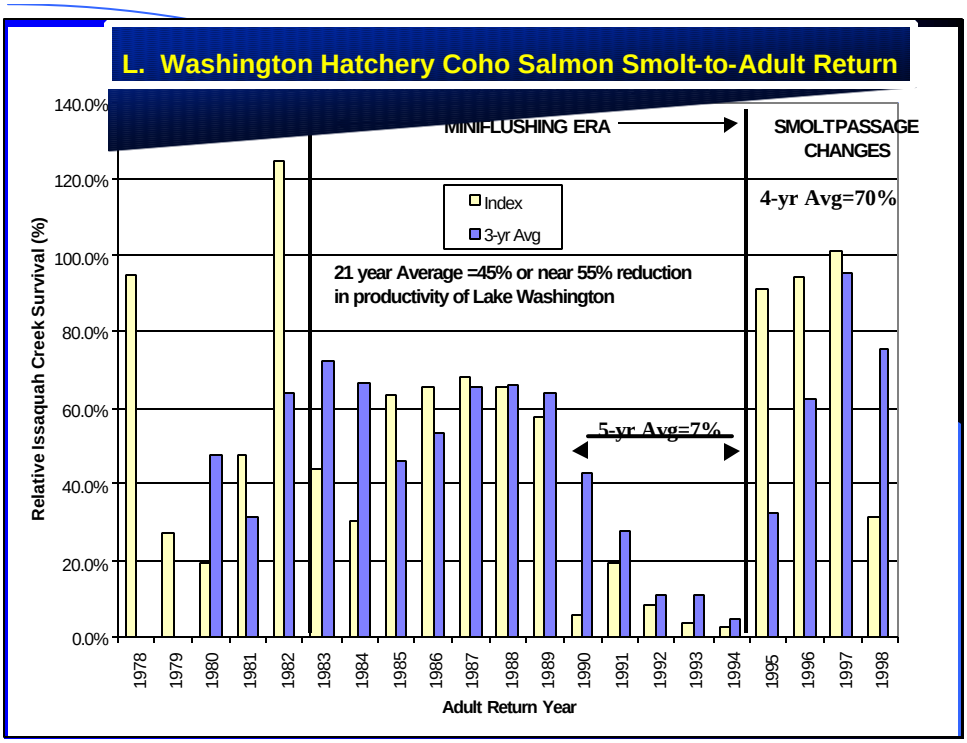
- Relative Smolt to Adult Returns (RSAR) - Coded-wire-tag hatchery smolt number/estimated adult return compared to parallel watersheds
- Example of RSAR for Hatchery Coho Salmon

This measure was used as a rule of thumb of what existing conditions were before implementation of the full restoration project. Hatchery coho salmon smolt to adult returns was calculated by WDFW. These values were compared (ratio) to year to year SAR for two hatcheries from parallel watersheds (Skykomish and Green River).

Returns show a clear trend of exceptionally lower survival from smolt migrations from 1989 to 1993 (about 7% RSAR). Returns after 1994 show a sharp increase (about RSAR 70%). The measure will be updated to include returns from smolt migration years since 2000.

- Recent Example from Sockeye Salmon (smolts emigrating in 2000)

The 1998 brood year had a forecast of 200,000 adults based on a spreadsheet model of estimated fry production to assumed smolt to adult survival. The actual return was 415,000 adults or a 210% higher return than expected. We can't identify the exact change that resulted in the higher survival but it coincides with the first year of full restoration actions at the Locks (except strobe lights).



New Tools to Estimate Survival

- Problem: Inability to monitor all outlets and to estimate overall project survival with precision.
- Tool Development: NMFS is currently working on developing a *miniature ultrasonic (acoustic) tag and tracking system* for tracking juvenile chinook salmon as small as 92 mm (phase I) with potential to reduce tag for fish to 70 mm (Phase II). Original impetus to develop the tag was to estimate survival through the Columbia River estuary from Bonneville Dam to the Mouth. The Locks is a small scale, more easily managed testing area for the tag and the tracking array.
- Application: This tag could be used in a variety of deepwater/saline environments including L Wash, LWSC (at Locks mean chinook size is=105 mm) , Shilshole Bay, and the nearshore throughout P. Sound.
- Experiment: The first pilot study of the entire system will be conducted in 2003 in the Ship Canal to determine effectiveness of this new system. Current expectation is for small-scale survival release using 60-80 tags and three fixed receiver nodes (4 hydrophones/node) and one mobile node to track fish.
- Constraint: Study plans will be finalized in February but equipment availability may not be known until March or April.

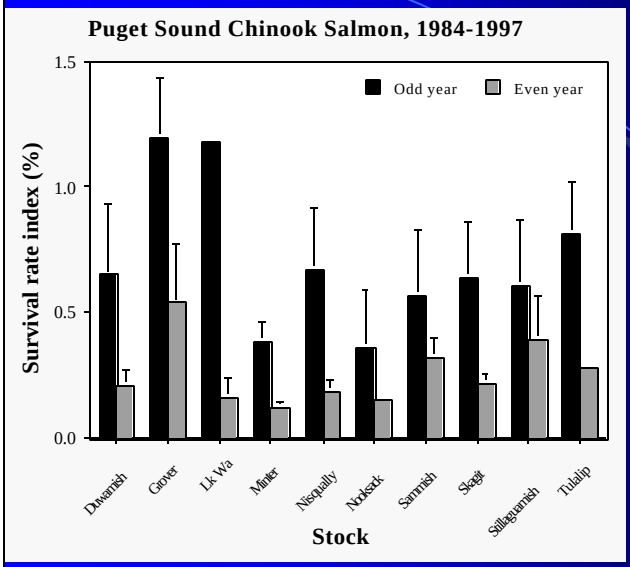
Acoustic Tag Study Components

- Downsize tag (currently underway)
  - battery, mother board, transducer
- Design and build detection array for the new tag that is calibrated to LWSC and Columbia River environmental conditions (design completed, building array)
- Design iteration between tag, detection array, biology, and statistical precision required for survival estimates
- Estimate survival using statistical models
  - Survival linked back to management question
  - Survival from Montlake to the Locks
- Migration behavior
  - passage times
  - areas of residency
  - habitat utilization
  - migration and passage routes

Other Factors Affecting Survival

- Hypothesis: Competition with pink salmon has led to reduced growth, delayed maturation, and reduced survival of Puget Sound chinook salmon.
- Method: The hypotheses were tested with release to recovery rates of coded-wire-tagged (CWT) subyearling chinook salmon, release years 1972-1997. These values are an index of survival.
- Survival indices of ten Puget Sound stocks (including Lake Washington), five Washington Coast stocks, three British Columbia mainland stocks, and four lower Vancouver Island stocks were examined.
- Condition: Puget Sound and the Fraser River support large numbers of odd-year adult pink salmon that produce numerous fry that emigrate to Puget Sound and Georgia Strait during even-numbered years; almost no pink salmon fry enter the sea during odd-numbered years.

Pink Salmon Abundance and Chinook Salmon Survival



- During 1984-1997, juvenile chinook salmon released during even-numbered years, experienced 62% lower survival compared with those released during odd-numbered years, a trend that was consistent among all 10 chinook salmon stocks.

Lower chinook survival was associated with large even-year migrations of juvenile pink salmon.

Conclusions – Juvenile Studies

- The Locks has become an ongoing experiment in adaptive management.
- Over 8 years we have conducted a continuing series of experiments in fish passage technology .
- These experiments included Hypothesis testing, development of a conceptual model of passage, appropriate monitoring methods and performance measures, evaluation of monitoring results, peer review of results, developing ecological models (adults) and continual feedback in modifying the project to improve performance.
- Current levels of juvenile RFGE may be approaching maximum values for most of the migration season, mid July to early August remain problematic for the final migrants.
- Results on monitoring other outlets (SW Drain) can be found at: http://www.nws.usace.army.mil/PublicMenu/Doc_list.cfm?sitename=lw_study&pagename=2002_Workshop
- Other factors can be affecting smolt survival soon after marine entry. CWT analysis suggests interspecific competition between abundant juvenile pink salmon and juvenile chinook may be resulting in marked lower adult returns every other year.

Adult Chinook Passage

Problem: Adult salmon hold at the Locks for up to 47 days in a small localized area immediately upstream of the Locks with unknown effect on reproductive success.

Hypotheses:

1) high water temperatures (and/or low dissolved oxygen) further upstream of the Locks are a barrier that adults will not swim through;

2) the area immediately upstream (within 1000 ft) of the Locks is a necessary cool water refuge where adults can safely hold until temperatures drop; and 3) what series of lock operations can improve the quality (dissolved oxygen, temperature, salinity) of the cool water refuge (and how do chinook respond to operational changes).

Adult Chinook Passage

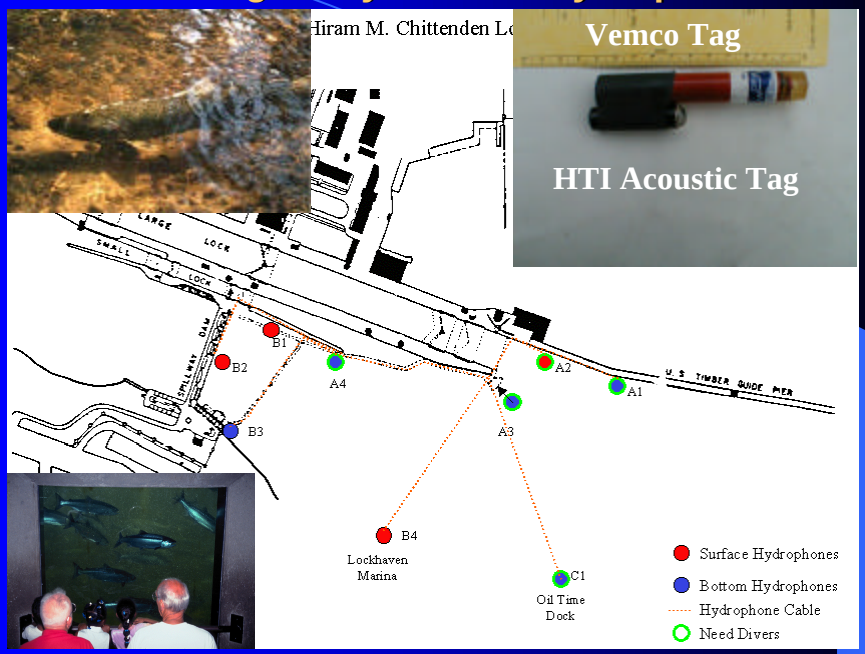
Experiment: A series of lock operation settings were developed and monitored to provide data to explore the second and third hypotheses. In 2000, adult chinook salmon behavior and water quality conditions were monitored during the operational testing.

Results:

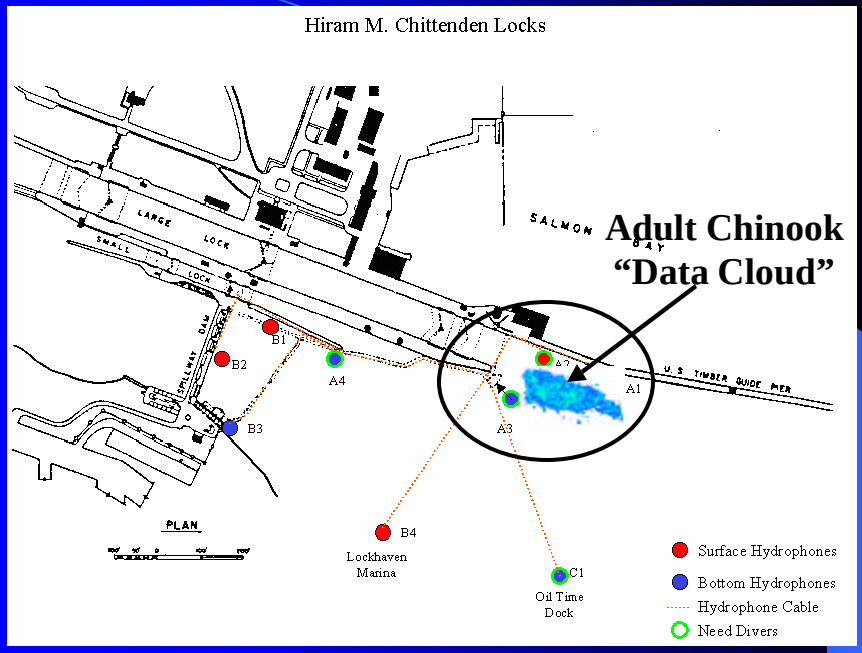
Initial analyses showed aggregate fish position

- 80% of all hours were spent in the vicinity of the drain and lock entrance
- Mean fish depth was 7.0-7.4 m and varied little from beginning of monitoring to end of monitoring
- In relation to water quality conditions the mean depth of fish was found at 1) salinity values of 0.5-1.0 ppt; 2) temperature of 20.5-21.5 C; and 3) dissolved oxygen levels of 7.5 mg/l at the beginning of the study and 6.7 mg/l at the end of the study.
- This level of analysis was considered insufficient to address the question of fish use in relation to environmental parameters.

Acoustic Tag Study: Linked Hydrophones



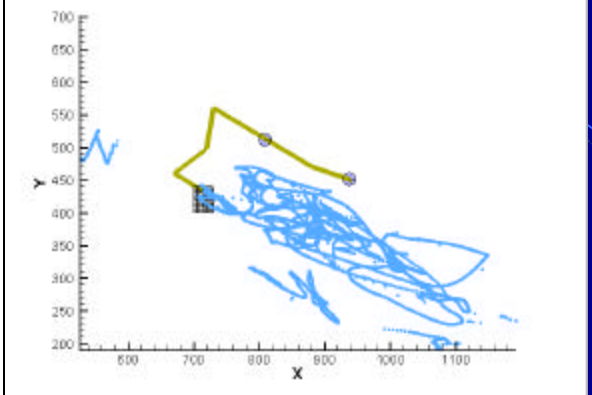
Planview of "Data Cloud" or Horizontal Position

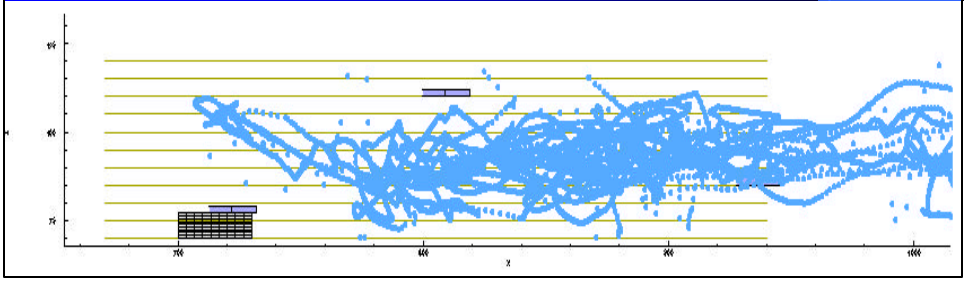


Adult Chinook "Data Cloud"

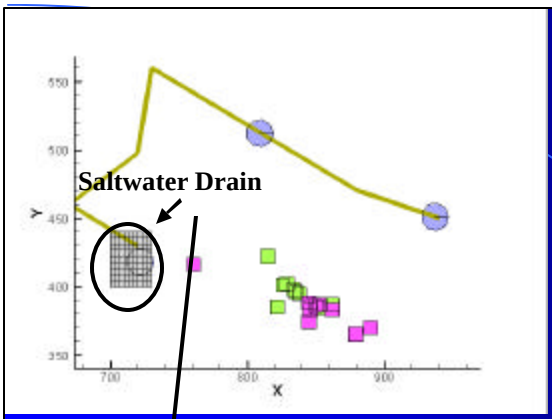
Make-up of the Data Cloud

Horizontal and Vertical Fish Tracks

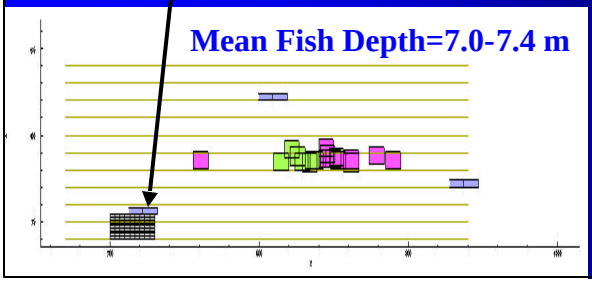




Acoustic Tag Study Vertical Position

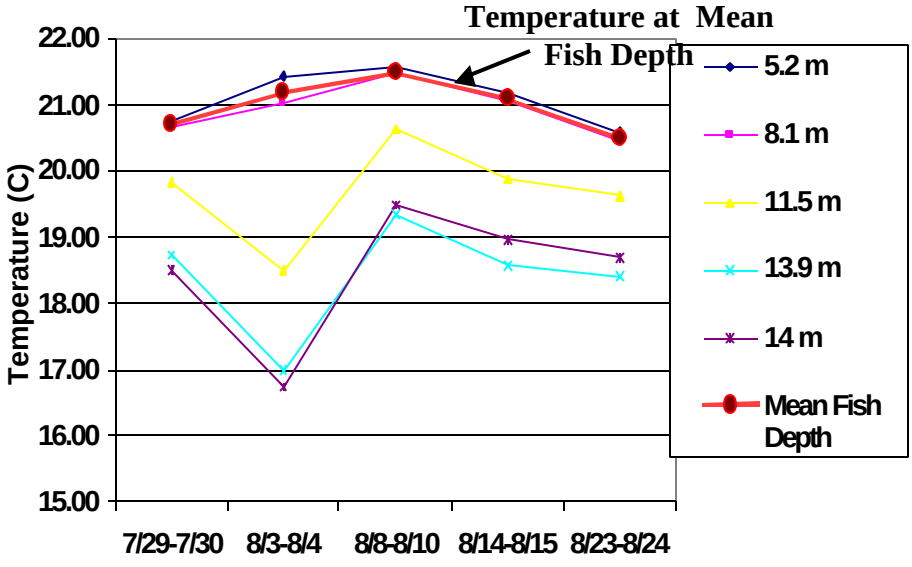


- Mean position of all echoes
- Mean position of echoes in close proximity to saltwater drain

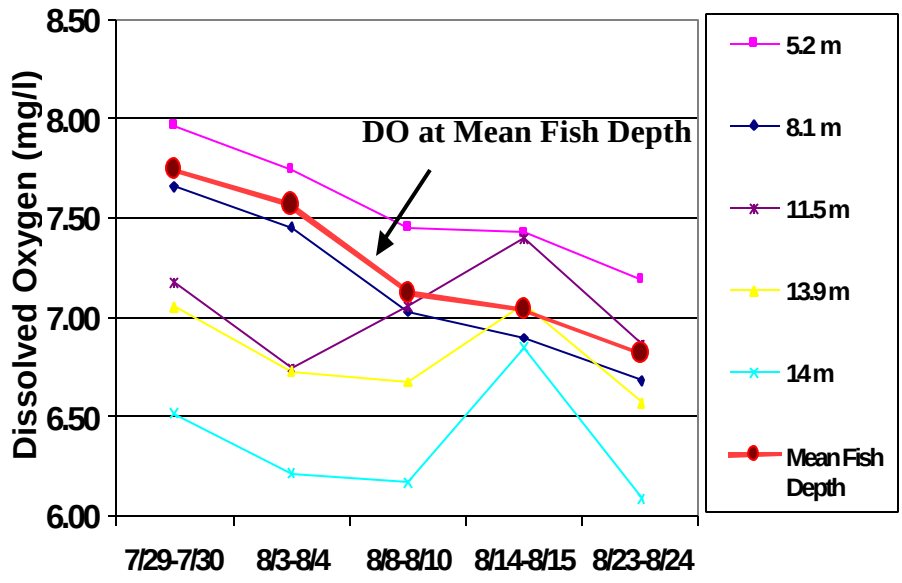


Next, integration with temperature, salinity, and dissolved O_2

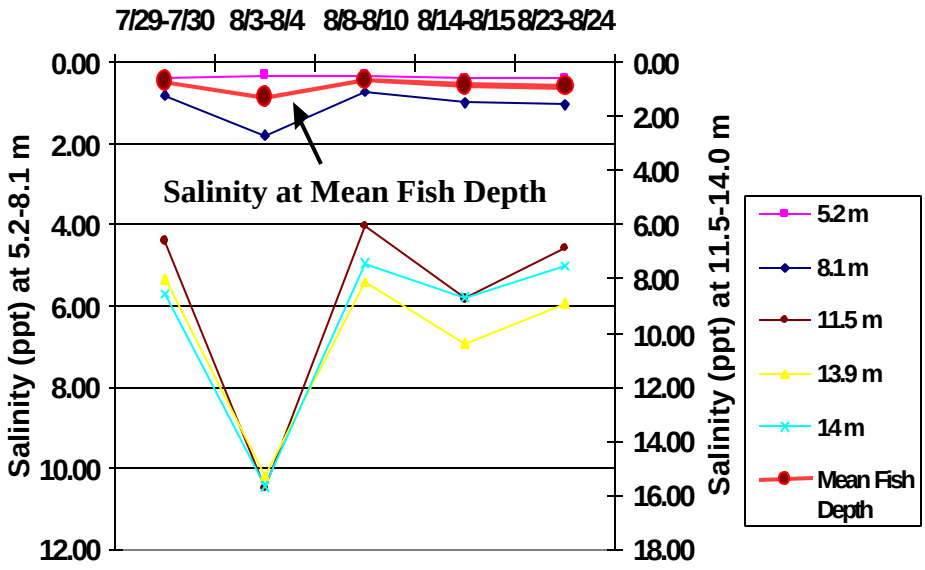
Vertical Fish Position vs. Water Temperature

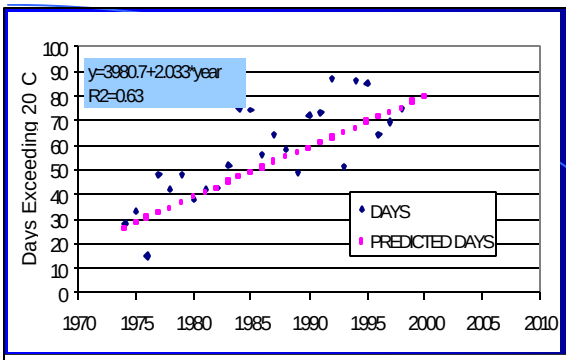


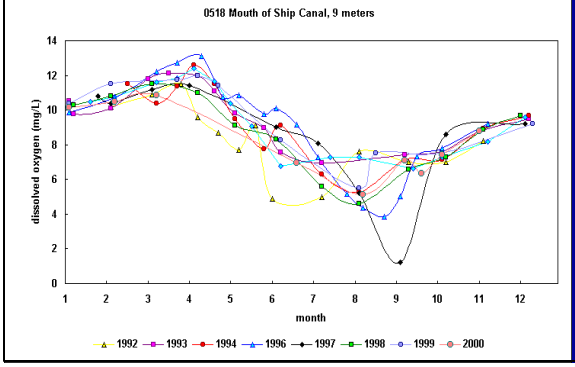
Vertical Fish Position vs. Dissolved Oxygen



Vertical Fish Position vs. Salinity







Adult Fish Passage

Increasing Water Temperature may be delaying adult migration

OR

Temperature And Low Dissolved Oxygen

OR

? ? ? ? ?

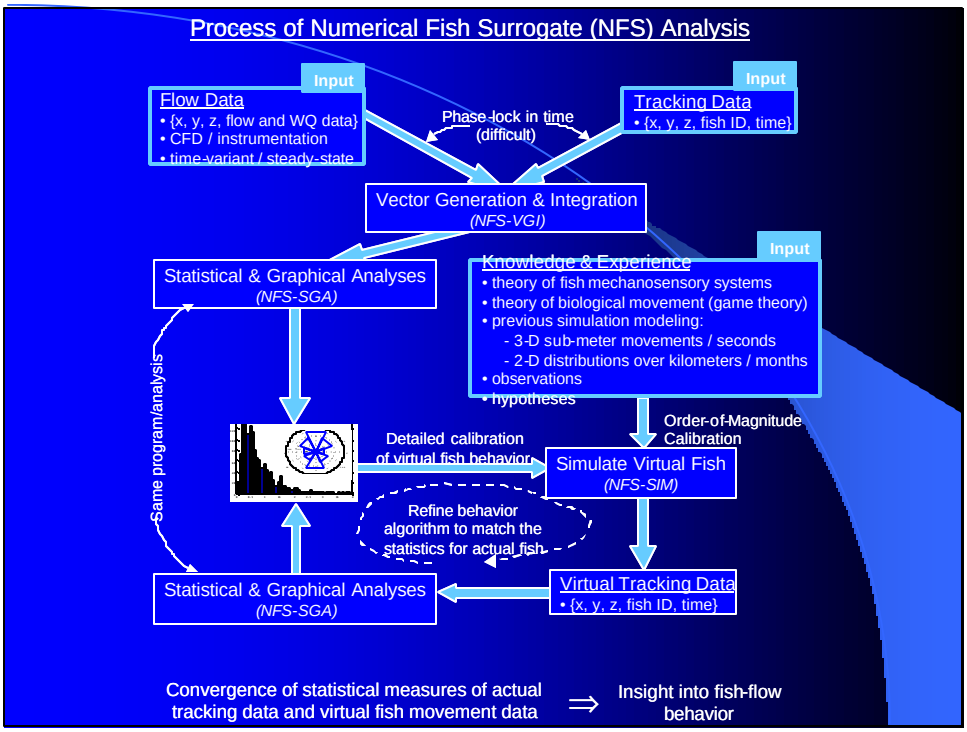
Coupled Ecological Model

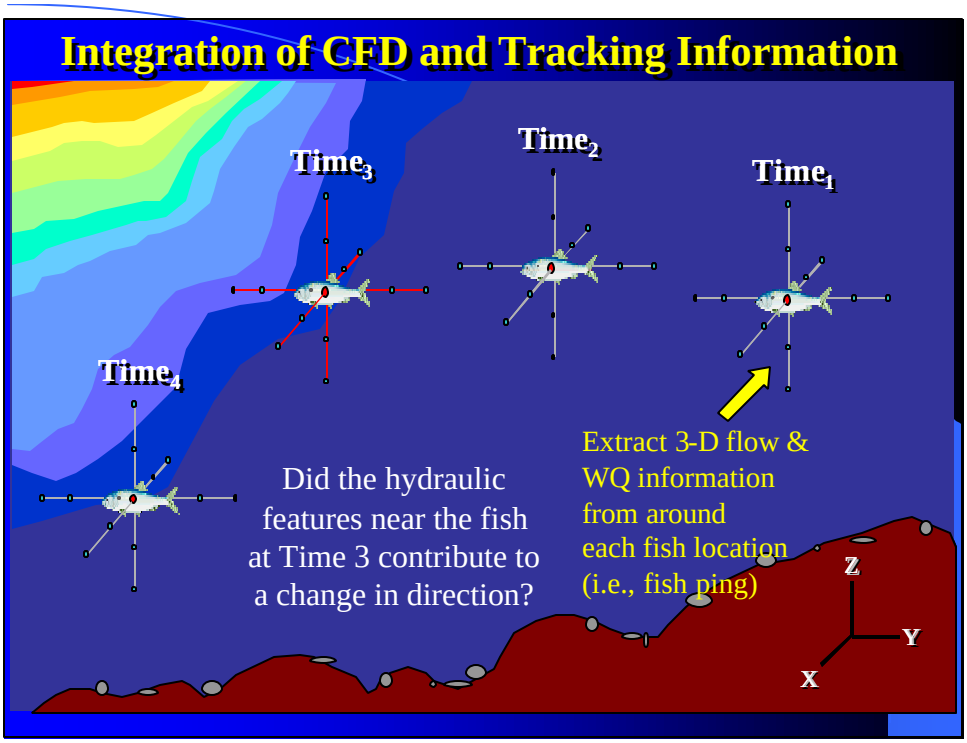
Problem:

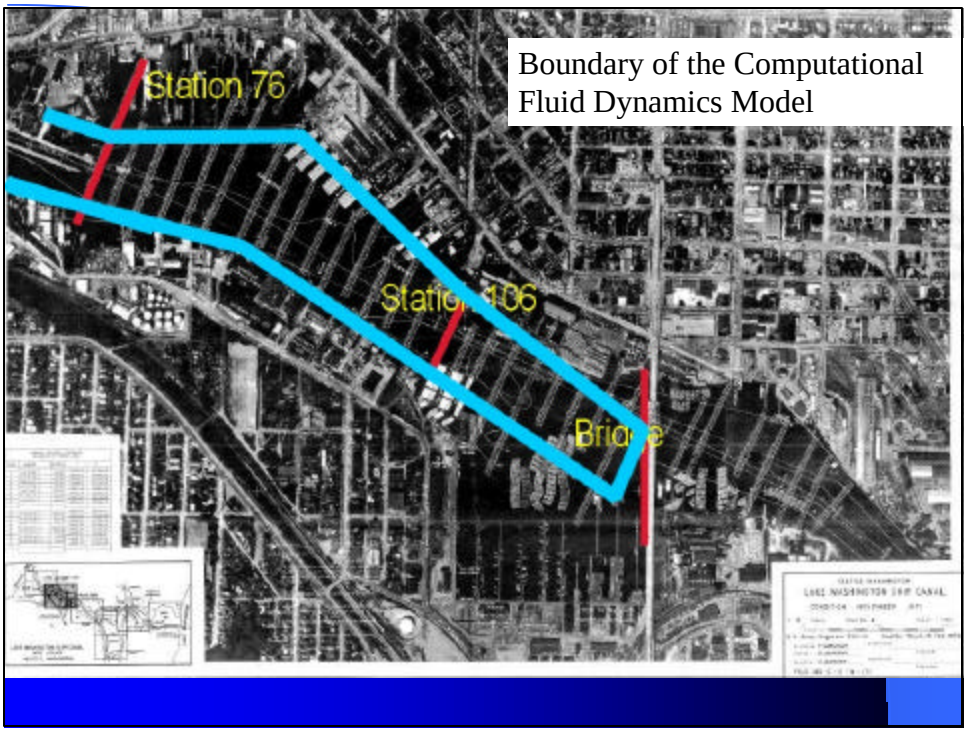
- **Unlike juvenile salmon studies to date, changes to Lock operations that might affect adult chinook could be tested using ecological modeling that should allow evaluation of adaptive actions without changes in locks structure or operation.**

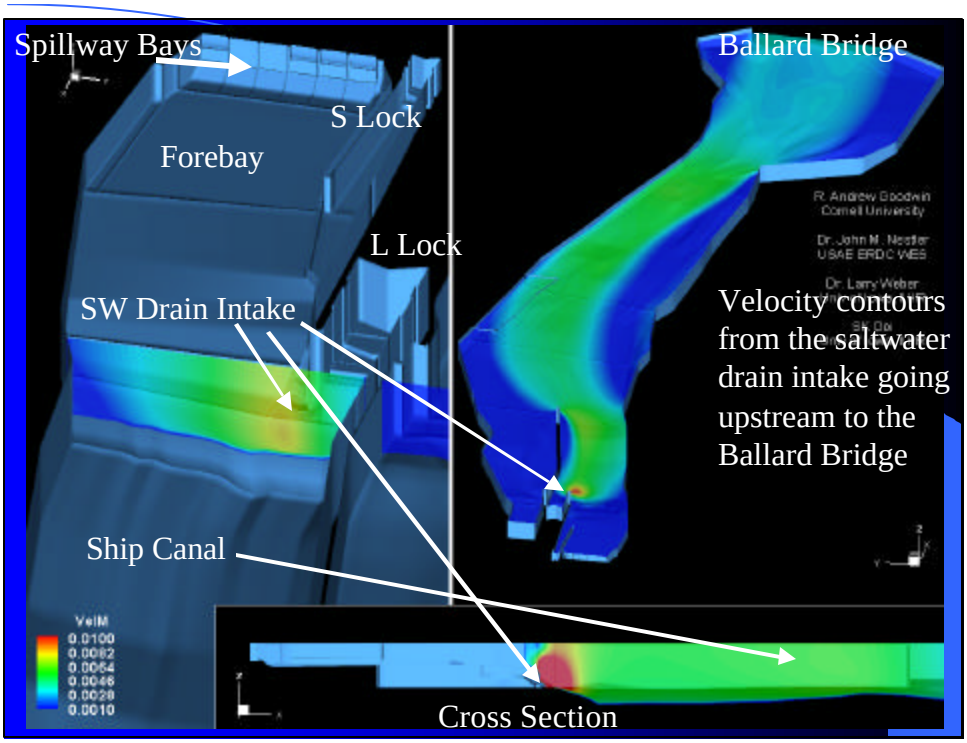
Method:

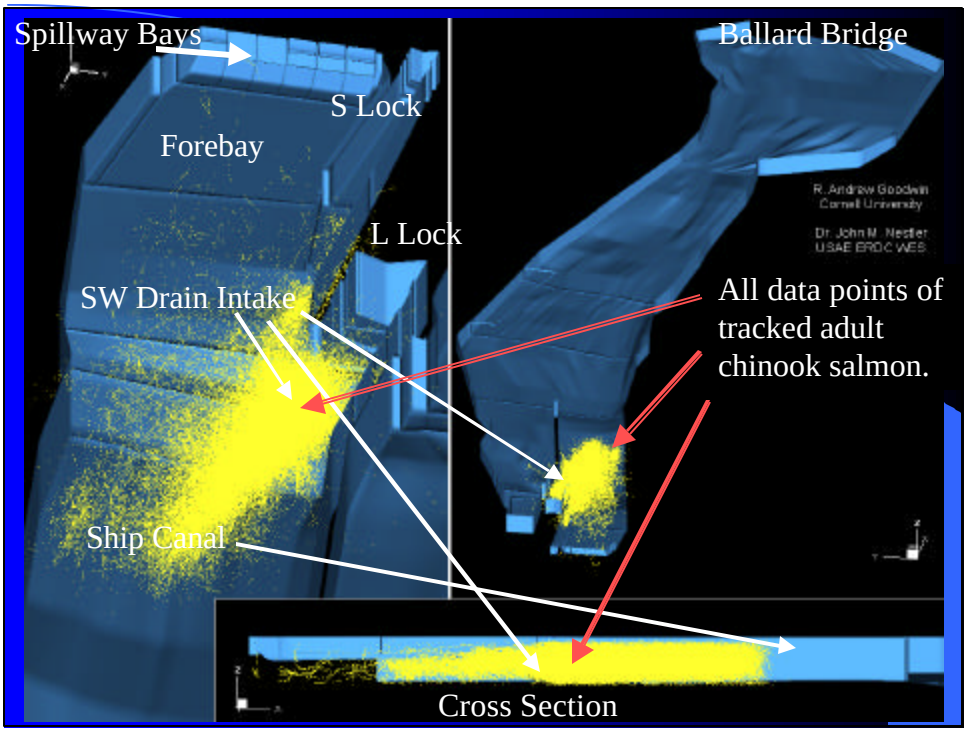
- **To evaluate the monitoring data a coupled ecological model linking a hydrodynamic model (computational fluid dynamics (CFD) model) of the Ship Canal and a fish behavior (numerical fish surrogate -NFS) model is being developed.**
- **This model can be used to further explore the monitoring data (fish behavior in response to environmental change), evaluate the hypotheses, and possibly to test and evaluate new scenarios of Lock operations or structural changes.**


Process of Numerical Fish Surrogate (NFS) Analysis
Input
Flow Data
• {x, y, z, flow and WQ data}
• CFD / instrumentation
• time-variant / steady-state
Phase-lock in time (difficult)
Input
Tracking Data
• {x, y, z, fish ID, time}
Vector Generation & Integration (NFS-VGI)
Statistical & Graphical Analyses (NFS-SGA)
Input
Knowledge & Experience
• theory of fish mechanosensory systems
• theory of biological movement (game theory)
• previous simulation modeling:
- 3-D sub-meter movements / seconds
- 2-D distributions over kilometers / months
• observations
• hypotheses
Order-of-Magnitude Calibration
Same program/analysis
Detailed calibration of virtual fish behavior
Simulate Virtual Fish (NFS-SIM)
Refine behavior algorithm to match the statistics for actual fish
Statistical & Graphical Analyses (NFS-SGA)
Virtual Tracking Data
• {x, y, z, fish ID, time}
Convergence of statistical measures of actual tracking data and virtual fish movement data
⇒
Insight into fish-flow behavior


Integration of CFD and Tracking Information
Time3
Time2
Time1
Time4
Did the hydraulic features near the fish at Time 3 contribute to a change in direction?
Extract 3-D flow & WQ information from around each fish location (i.e., fish ping)
Z
Y
X


Station 76
Boundary of the Computational Fluid Dynamics Model


Spillway Bays
Ballard Bridge
S Lock
Forebay
L Lock
SW Drain Intake
Velocity contours from the saltwater drain intake going upstream to the Ballard Bridge
Ship Canal
Cross Section



Conclusions – Adult Studies

- Studies on adult chinook salmon have followed the example set by our juvenile studies.
- We used a pilot technology (a linked hydrophone array) to accurately track adult chinook in a very small localized area.
- Adult studies have moved beyond actual physical testing and monitoring of results and are attempting to employ ecological modeling as an adaptive evaluation tool.
- The expectation is that the model can be used to quantitatively evaluate each possible operational scenario or design alternative considered for the Locks by using virtual fish programmed to respond according to rules (statistical relationships) uncovered during the system analysis of the integrated fish behavior and flow/water quality data sets.
- This latter step has only been achieved at a reasonable level for salmon in one other project (Lower Granite) so there is some uncertainty as to the success for the Chittenden Locks. However, if successful, this would take much of the uncertainty out of salmon restoration activities that involve major hydraulic redesign or changes in water management practices.